UNITED STATES NAVY

PROJECT SQUID

TECHNICAL MEMORANDUM No. PR-8

THE PRINCETON PILOT
VARIABLE DENSITY
SUPERSONIC WIND TUNNEL

BY

SEYMOUR M. BOGDONOFF

29 MAY 1948
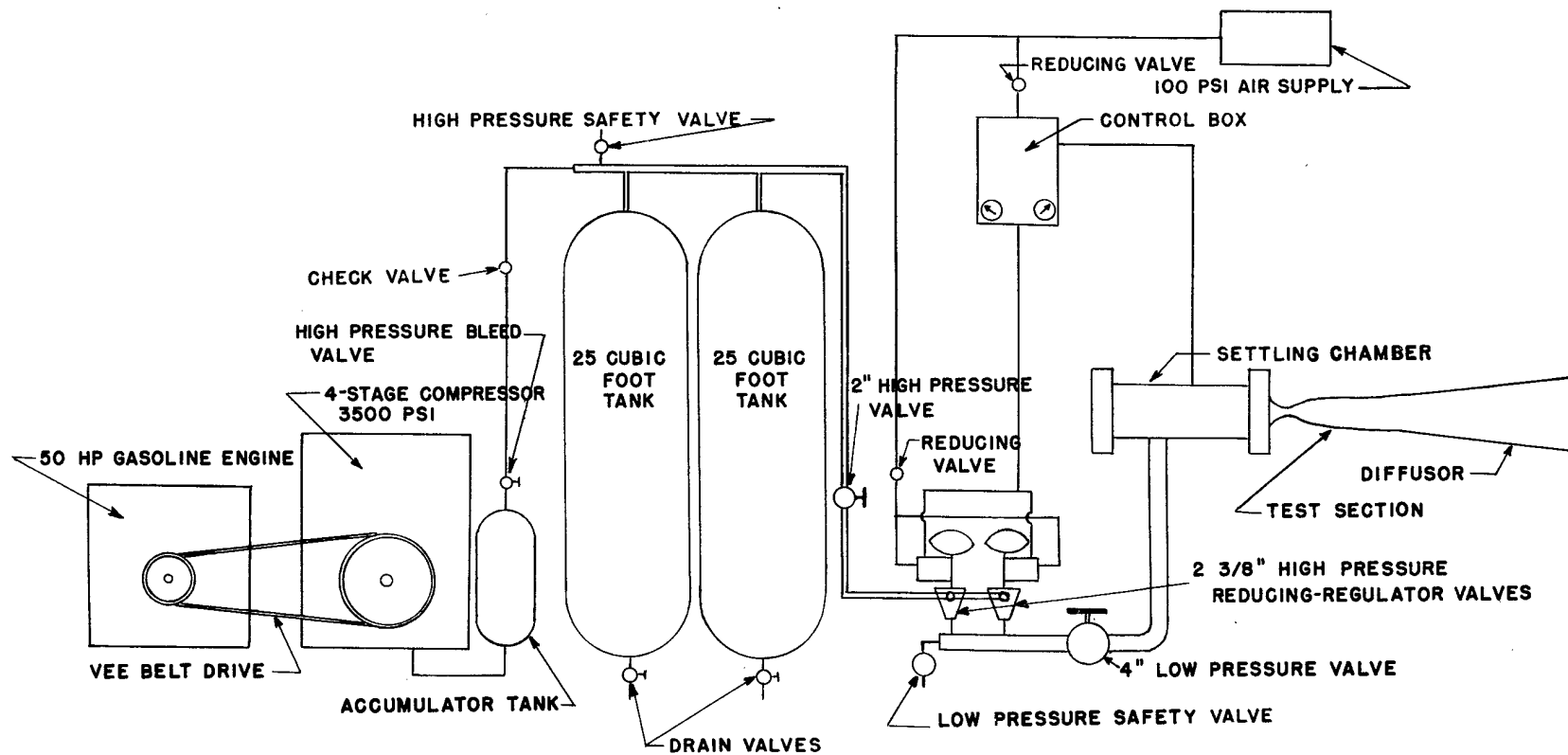
PRINCETON UNIVERSITY

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United States Navy

PROJECT SQUID

A COOPERATIVE PROGRAM

OF FUNDAMENTAL RESEARCH IN JET PROPULSION

FOR THE

OFFICE OF NAVAL RESEARCH

OF THE

NAVY DEPARTMENT

CONTRACT N6-ori-105, TASK ORDER III, PHASE 1

NR 220-038

Technical Memorandum No. PR-8

HIGH PRESSURE SAFETY VALVE

REDUCING VALVE
100 PSI AIR SUPPLY

CONTROL BOX

CHECK VALVE

HIGH PRESSURE BLEED
VALVE

SETTLING CHAMBER

4-STAGE COMPRESSOR
3500 PSI

25 CUBIC
FOOT
TANK

25 CUBIC
FOOT
TANK

2" HIGH PRESSURE
VALVE

REDUCING
VALVE

50 HP GASOLINE ENGINE

DIFFUSOR

TEST SECTION

2 3/8" HIGH PRESSURE
REDUCING-REGULATOR VALVES

VEE BELT DRIVE

4" LOW PRESSURE VALVE

ACCUMULATOR TANK

LOW PRESSURE SAFETY VALVE

DRAIN VALVES

PROJECT SQUID

Technical Memorandum No. PR-8

THE PRINCETON PILOT

VARIABLE DENSITY

SUPERSONIC WIND TUNNEL

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29 May 1948

AERONAUTICAL ENGINEERING LABORATORY

PRINCETON UNIVERSITY

PRINCETON, NEW JERSEY

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ACKNOWLEDGMENT

SUMMARY

The design and operation of the pilot variable density super-
sonic wind tunnel of Princeton University's Aeronautical Engineer-
ing Laboratory are discussed in some detail. The tunnel, with a
1 x 2½ inch test section, is designed to operate with stagnation
pressures up to 500 psi at Mach numbers from 1.5 to 5.0. It is of
the blow-down type, but uses a pressure control system to keep the
stagnation pressure constant during a test. Schematic drawings of
the equipment and photographs are presented and a short discussion
of the preliminary tests is included. The main result is the obser-
vation of a transient at starting due to heat transfer effects.
This transient can be almost completely eliminated by precooling
the tunnel with a small amount of cold air. Operation of all e-
quipment was satisfactory.

THE PRINCETON PILOT VARIABLE DENSITY
SUPERSONIC WIND TUNNEL

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INTRODUCTION

Experimental investigations have shown that to simulate accurately the flow over wings and bodies of full scale airplanes, the Reynolds and Mach numbers of the test model must be the same as those of the full scale unit. In subsonic aerodynamic testing, high Reynolds numbers have been obtained by using large scale tunnels or by operating smaller tunnels at high pressure levels. A continuously operating tunnel at supersonic speeds, however, using either of these methods necessitates a prohibitive amount of power. So, supersonic tunnels now operating are relatively small and operate with test sections at less than or near atmospheric pressure. The Reynolds numbers are consequently quite low, and no tunnel is now in operation which can attain Reynolds numbers above approximately eight million. In addition, the tunnels attaining the highest Reynolds numbers necessarily do so at low supersonic Mach numbers, approximately 1.7. Since the high speed airplanes of tomorrow will operate at Reynolds numbers above fifty million and at Mach numbers up to perhaps 4 or 5, there is a serious gap between the obtainable data and the actual flight conditions which will be experienced.

The alternative to the low pressure continuously operating tunnel is the intermittant or blow-down tunnel. In this type of tunnel, the energy required to produce a supersonic stream is accumulated by using a small amount of power over a long period of time to either pump up or evacuate a large tank. Supersonic blow-down tunnels are of two main types: (1) A pressurized tank is exhausted through the tunnel to the atmosphere, and (2) An evacuated tank sucks air from the atmosphere through the tunnel. It is, of course, possible to have a combination of the two. In the former, the stagnation pressure and temperature constantly change during the run as the tank pressure falls, while in the latter, the stagnation pressure and temperature are constant and equal to atmospheric pressure and temperature. To study the effects of Reynolds number over a very wide range, the pressure level in the tunnel must be easily adjusted yet remain constant for a fixed time at any level.

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The Aeronautical Engineering Laboratory of Princeton University has been working on a supersonic tunnel of the blow-down pressure tank type, but with a few innovations which greatly increase its testing value. The pressure in this tunnel is held constant for a certain length of time by a regulator-reducing valve control system installed between the high pressure air supply and the tunnel. The tunnel has been constructed to get basic information on the operation of this type of tunnel as well as to provide a means of making preliminary studies of certain supersonic phenomena.

The technical design and operation of this pilot tunnel are discussed in some detail in the following sections, and experimental results are presented for the preliminary calibration tests. The detailed drawings of the pilot tunnel, made under the direction of the author and some of the design calculations are presented in Princeton University Aeronautical Engineering Laboratory Report No. 121, *The Design of a Supersonic Blowdown Pilot Tunnel With a Mach Number 3.01 Nozzle* by R. C. Scott, October, 1947.

RESEARCH PROBLEMS

In addition to the primary purpose of this equipment, the study of a supersonic tunnel which will operate over a wide pressure range, many other fundamental studies can be made with little or no change in design. A few investigations which will be carried out in the near future are:

1. The evaluation of the effect of Reynolds number on the boundary layers in nozzles and the subsequent variation in Mach number with variation in the stagnation pressure level.

2. The determination of the limiting Mach number which can be obtained without preheating of the air. Theoretical calculations by Lees and Charyk and others have shown that above Mach numbers of approximately 4.5 there is the possibility of condensation of a component of the air itself. To determine the validity of these calculations and consequently the amount of heating that would be needed to get higher Mach numbers is of great importance in the design of high Mach number wind tunnels. This investigation will probably include testing with pure gases such as nitrogen or helium.

3. The fundamental study of boundary layers on flat plates, in corners, and around wedges and cones, over as wide a range of Reynolds numbers as possible. This study to cover the laminar boundary layer as well as the turbulent.

4. The study of the effects of shock waves of various strengths on the boundary layer in an attempt to clarify the shock wave-boundary layer interaction. Very little theoretical information is available on this phenomena, but preliminary studies indicate that the boundary layer thickness as well as its character, laminar or turbulent, are important factors.

5. The interaction of two or more shock waves has been studied quite extensively in shock tubes at atmospheric pressures. Qualitative disagreement with the existing theories has been found for weak triple shock waves and it is believed that part of this discrepancy may be due to the viscous interaction at the point where the three shocks interact. A series of experiments made over a wide pressure range should indicate whether the viscous forces at this point actually account for the discrepancies.

PILOT TUNNEL DESIGN

The size of the compressors, tanks, and test section were dictated by four requirements:

1. Runs of at least 20 seconds duration. In this length of time it is believed that the operating controls and the flow would stabilize and still leave sufficient time to photograph the recording instruments.

2. Sufficient capacity to provide at least one run per day.

3. A minimum test section size of one by two and a half inches.

4. Stagnation pressure from 30 to 500 pounds per square inch absolute with no structural limitation preventing pressures up to 900 pounds per square inch.

The fulfillment of these requirements gave the following system shown schematically in Figure 1, Frontispiece. A 50 horsepower four-stage compressor pumps two 25 cubic foot tanks up to any desired pressure below 3500 pounds per square inch. Two three-eighths inch high-pressure reducing-regulator valves, with special control systems, hold the settling chamber pressure constant at any value from 30 to 500 pounds per square inch. The air leaves the settling chamber through a converging section where the velocity increases to a Mach number of approximately 0.4. The two-dimensional section downstream of the converging section is made up of a nozzle designed to accelerate the air to the desired Mach number at the entrance to the straight one by two and a half inch test channel. The air then passes through a diffuser and silencer which exhausts to the atmosphere.

Figure 2, page 4, shows a chart of approximate running time versus Mach number for the tunnel when the tanks are pumped to 3200 pounds per square inch and the settling chamber pressure is 500 pounds per square inch. This curve assumes instantaneously operating valves, isentropic expansion in the tanks and an adiabatic throttling process in the regulating valves. The minimum time requirement, a 20 second run, is met for all conditions; although at a Mach number of 1.5 where the throat area is largest, this condition is just satisfied. Since the running time is inversely proportional to the stagnation pressure, operating times well over the minimum can be obtained for most conditions. With the stagnation pressure range avail-

OPERATING TIME, SECONDS (vertical axis, 0 to 300)
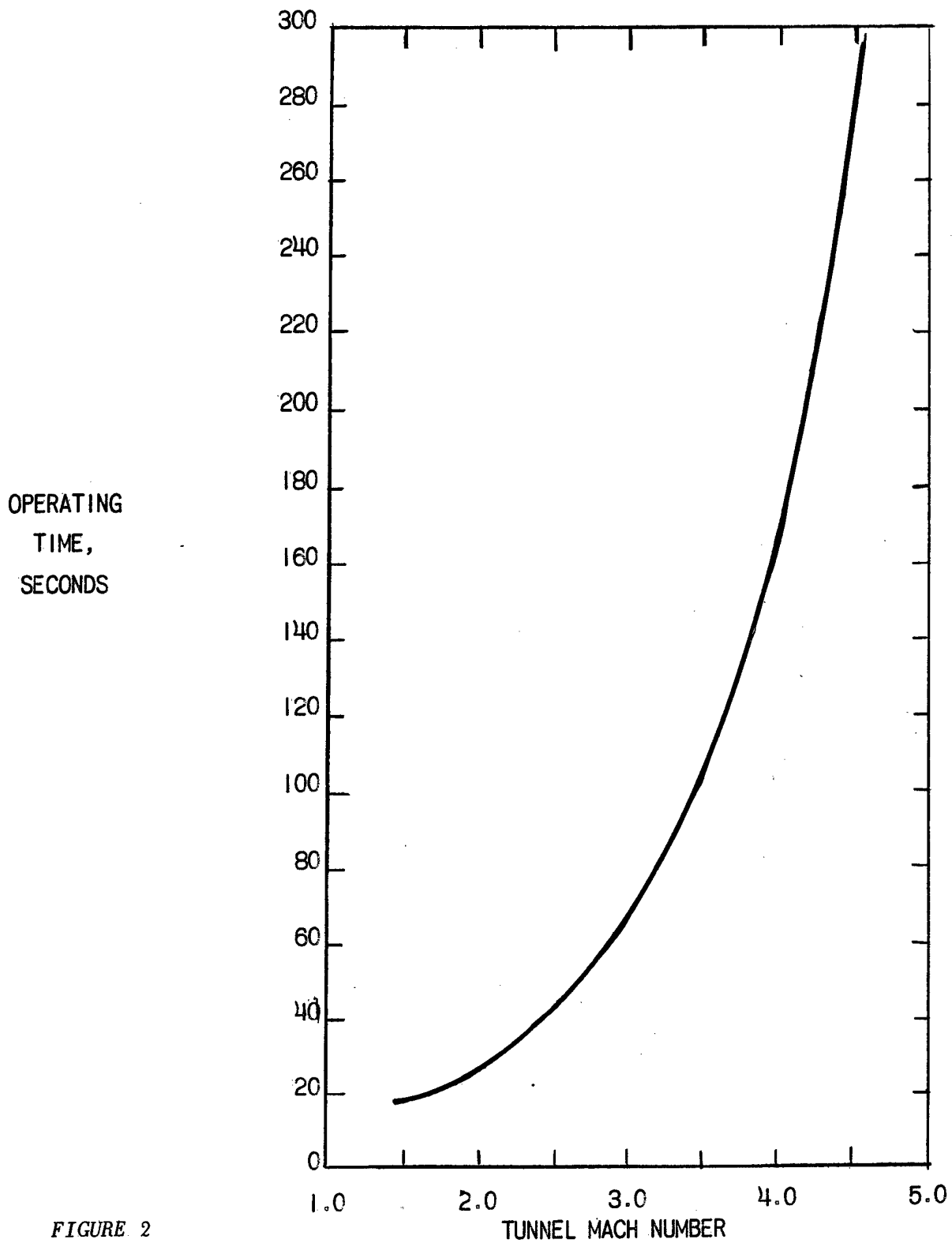
TUNNEL MACH NUMBER (horizontal axis, 1.0 to 5.0)

FIGURE 2

Tunnel running time versus Mach number; 3200 psi in storage tanks, 500 psi in settling chamber, isentropic expansion in tanks, adiabatic throttling process through regulator valves which open instantaneously.

able, and the structure designed to go to still higher pressures, the ratio of maximum to minimum Reynolds numbers which can be investigated is over ten to one with a fixed model. An even wider range can be covered by changing the scale of the model.

TUNNEL OPERATION

The general procedure for the operation of the tunnel is as follows: The compressor is allowed to run until a pressure of approximately 3000 pounds per square inch is reached in the accumulator tank which is mounted on the compressor. The valve to the charge line is then opened allowing the additional air pumped into the accumulator tank to flow through the charge line to the two 25 cubic foot storage tanks. At frequent intervals, the after-coolers on each stage of the compressor are drained. The compressor continues to run until the storage tank pressure is of the desired value, or 3200 pounds per square inch, at which time an automatic cut-off shuts off the engine. The charge line valve is closed, and the tunnel is then ready for operation. The tunnel may be started by slowly increasing the pressure in the settling chamber to the desired pressure, or by presetting the pressure in the control box and then turning on the control air. This latter method is quite fast, the tunnel reaching equilibrium conditions, evidenced by cessation of fluctuation of the pressure gages, in approximately six to ten seconds. The cameras are then tripped to photograph the two instrument panels and the spark system is tripped to take the Schlieren or shadow picture. Usually two sets of data are taken approximately 20 seconds apart to check the consistency of the data. The tunnel will continue to operate at constant pressure until the pressure in the tanks drops to a point where the regulator valves will no longer pass the desired mass flow. Usually runs of one to two minutes are made, but complete data can be taken in approximately 15 seconds. The two-inch high-pressure valve in the header between the storage tanks and the regulators is then closed and the compressor is started to recompress the air if another run is to be made. The time for recompression is not more than two hours, since there is usually some pressure left in the tanks at the end of the run.

DETAILED DESCRIPTION OF EQUIPMENT

Compressors and Tanks. The compressor is an Ingersoll-Rand, Model 40, four-stage high pressure positive displacement unit (size 6" & 6" & 3" & 2" & 1 1/8" x 5"), which will deliver twenty cubic feet of air per hour at 3000 pounds per square inch. It is driven by a Waukeska six cylinder gasoline engine which develops fifty horsepower (Model 6-BZU). The compressor is

provided with its own liquid cooling system and after-coolers after each stage of compression. These coolers are quite efficient, keeping the air temperature at the exit of the fourth cooler down to within 10 to 15 degrees of room temperature. Mounted on the compressor base is a six cubic foot accumulator tank into which the fourth stage cooler exhausts and from which the air is bled to the two storage tanks. By keeping the valve in the charging line closed, the compressor pumps the accumulator tank to 3000 pounds per square inch, at which time the valve in the charging line is opened just enough to bleed the excess air into the storage tanks. By keeping the accumulator tank at 3000 pounds per square inch and close to room temperature, most of the water and oil vapor condenses. Calculations show that if the air in the accumulator tank is saturated, there is only one part of water vapor to approximately twelve to fifteen thousand parts of air. This is about as good as the best chemical dryers have been able to do. Thus the compressor serves also as an efficient air dryer and oil remover. Each stage of the compressor is provided with a safety valve and a high-pressure limit switch which cuts off the engine if the tank pressure goes above 3200 pounds per square inch.

From the accumulator tank, a charging line runs to the manifold system connecting the two storage tanks and the regulator system. The storage tanks, Figure 3, page 7, which were constructed by the A. O. Smith Corporation for the Navy are torpedo charging tanks designed to operate at 3000 pounds per square inch and hydraulically tested to 5000 pounds per square inch. Each has a 25 cubic foot capacity and is approximately ten and a half feet high and thirty inches in diameter. A drain valve at the bottom of each tank is provided to check for water or oil condensation.

Reducing-regulator system. The reducing-regulator system was designed by the Hammel-Dahl Company using two 3/8 inch high pressure reducing valves operating in parallel. The valves are driven by special diaphragms and a separate air supply controlled by a Hanlon-Waters control system. The installed regulators are shown in Figure 4, page 8, and the control box in Figure 5, page 9.

A simplified schematic diagram of the control system is shown in Figure 6, page 9. The bourdon tube, which is mounted on a set of planetary gears, is set by means of the control knob to give the required chamber pressure. When the control knob is set at zero, the bourdon tube link holds the throttle arm off the bleed nozzle. The nozzle is then wide open, allowing all the supply air which passes through the orifice to escape and no impulse is sent to the reducing-regulator valves which stay closed. If the bourdon tube is rotated to increase the pressure in the settling chamber, the throttle arm closes the bleed nozzle and allows a pressure to build up above the upper diaphragm. As this diaphragm deflects, it opens the main control valve by the link connecting the upper and lower diaphragms. With the main control valve open, the pressure on the diaphragms of the reducing-regulator valves
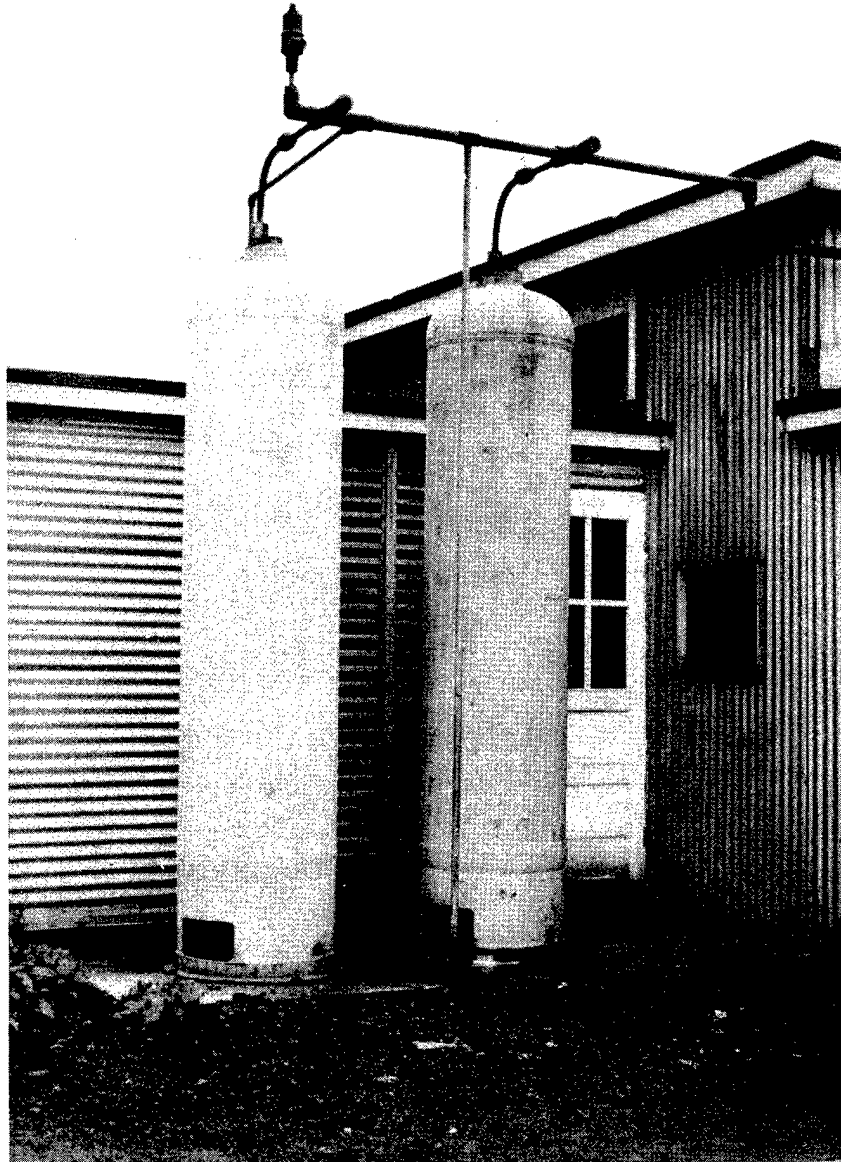
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FIGURE 3

Photograph of the two 25 cubic foot storage tanks showing the high pressure relief valve at the end of the header connecting the tanks to the valve system in the test room at the right.
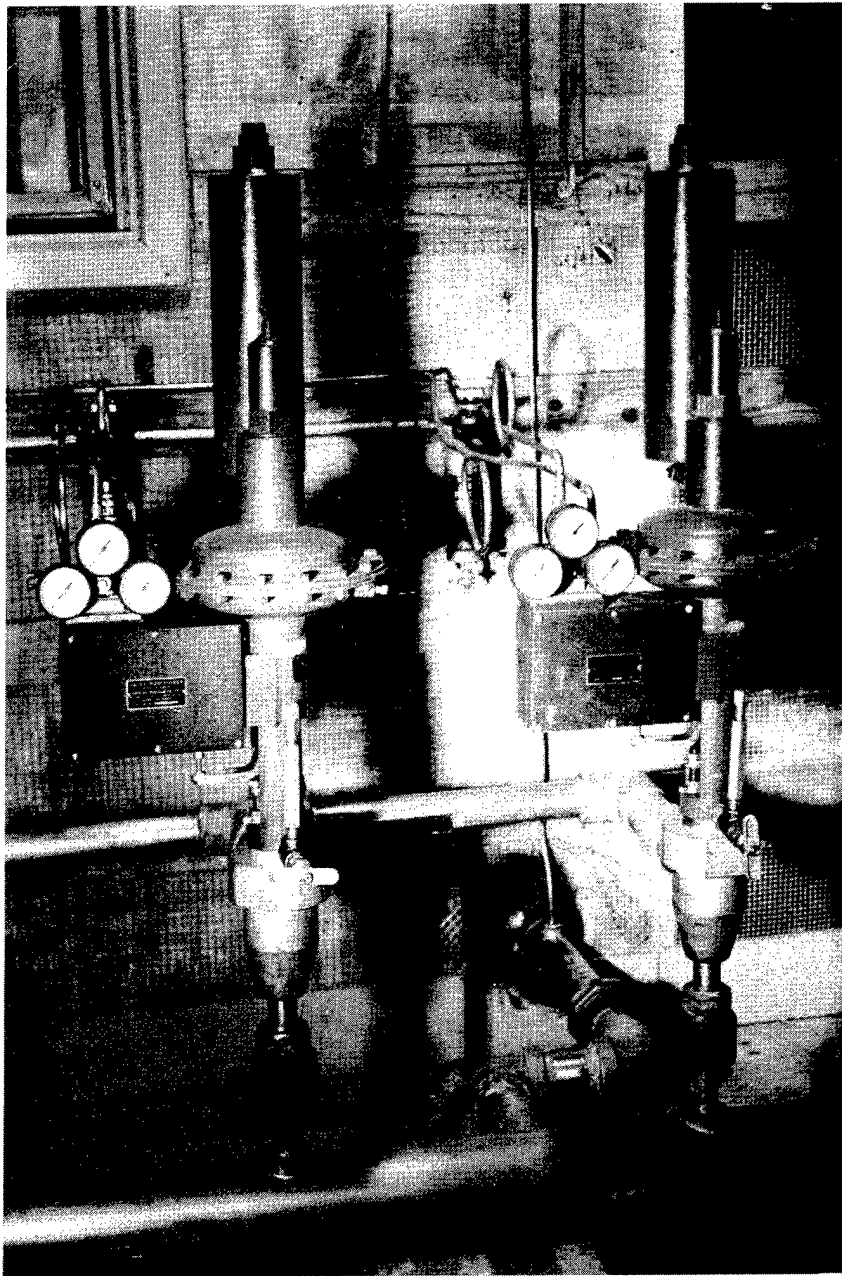
FIGURE 4

Photograph of the two reducing-regulator valves showing the damping tanks mounted above the diaphragm domes and the valve positioners mounted on the left of each valve. The high pressure air enters from the header at the rear, the low pressure air dumping into the four-inch header at the bottom of the photograph.
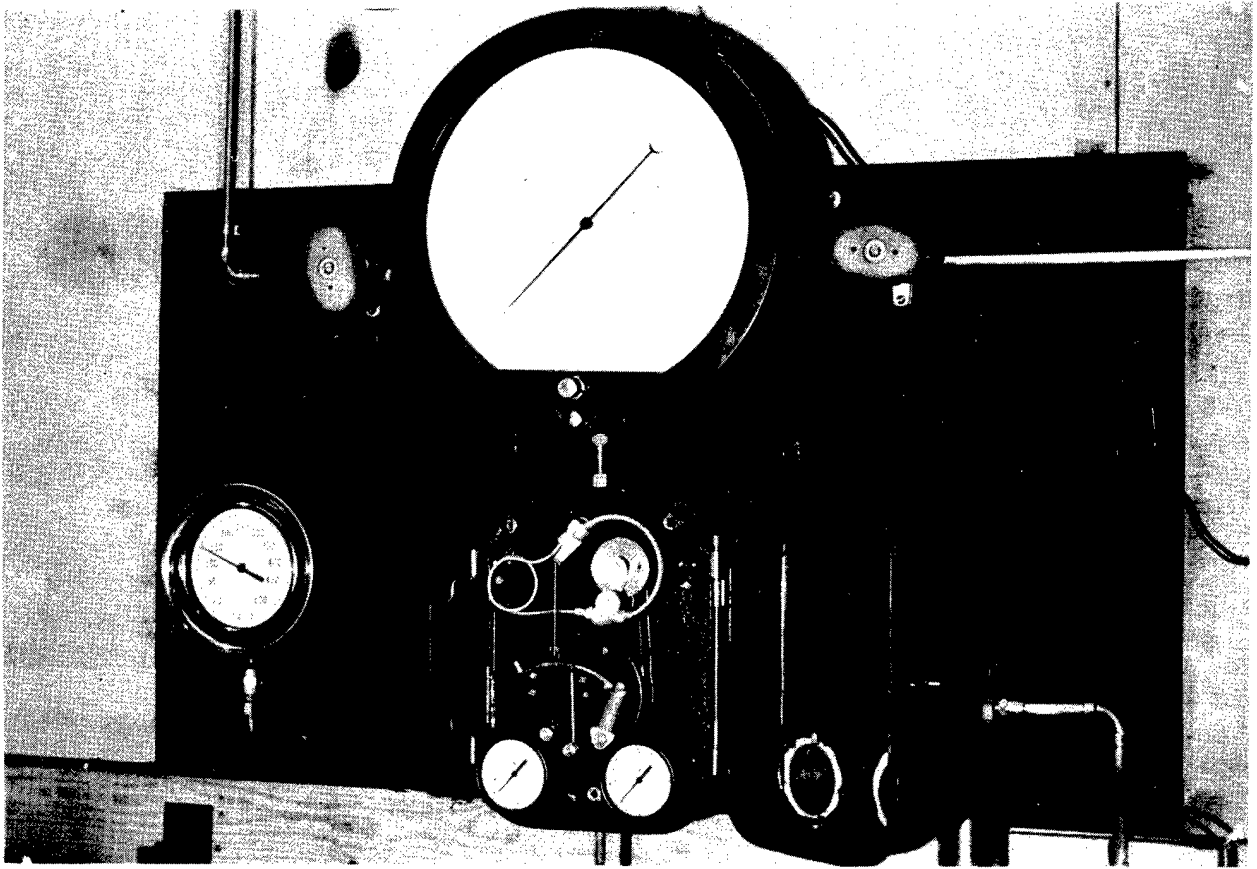
FIGURE 5

*Photograph of the control panel showing the control box with the door open. The large
gage above the box indicates the controlled pressure (settling chamber pressure) and the small
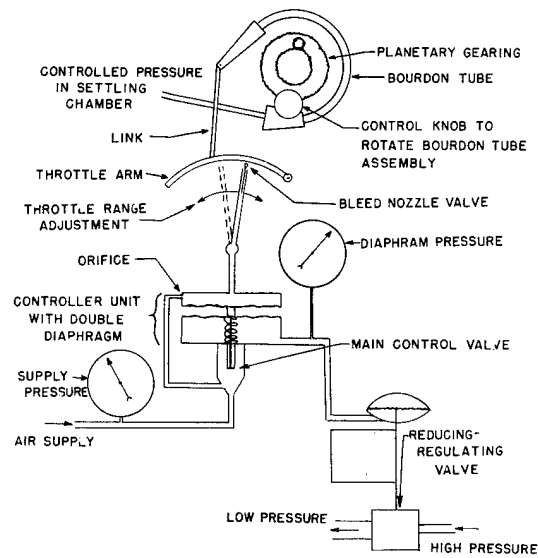gage on the left shows the control air supply pressure.*

FIGURE 6

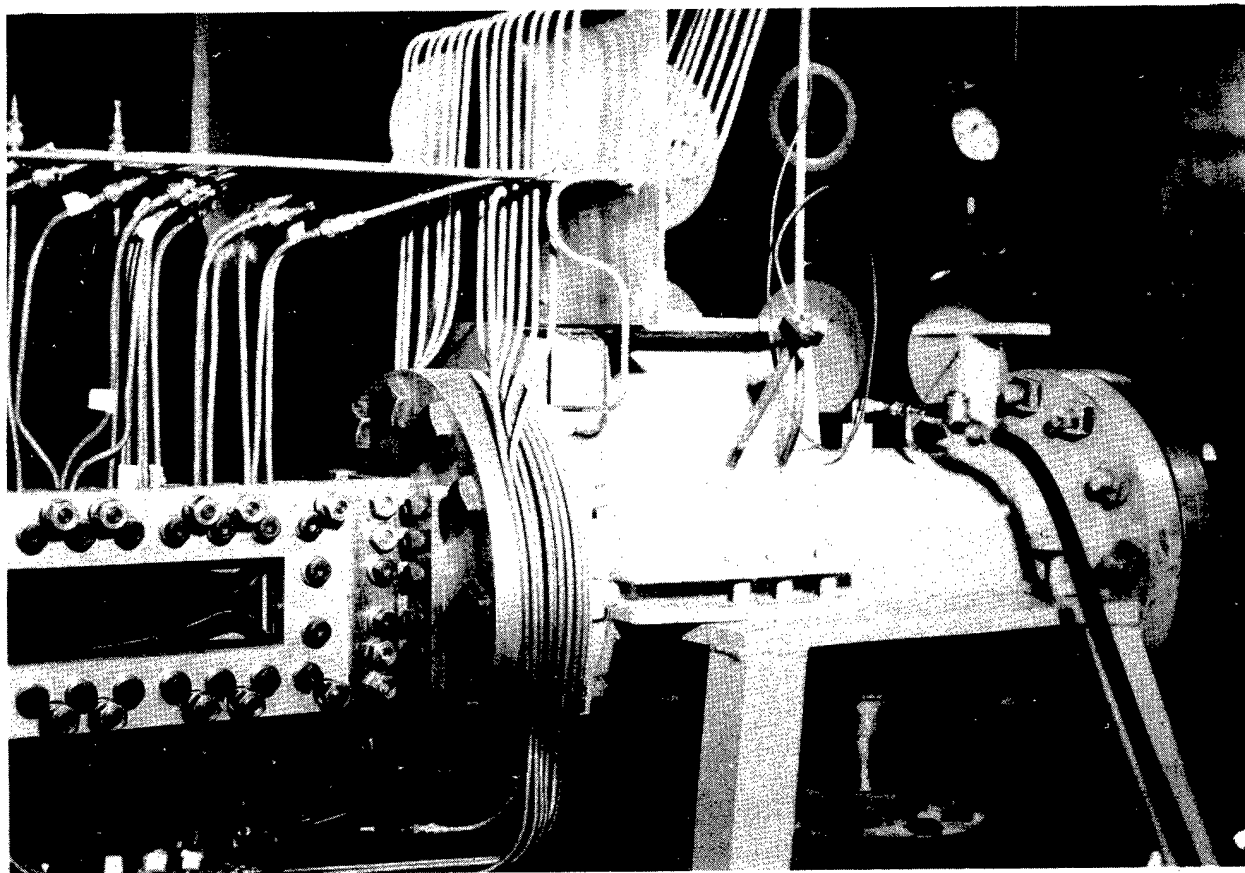*Schematic diagram of the pressure control system.*

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FIGURE 7

Photograph of the settling chamber showing the installation of the thermocouple and control pressure line in the side of the settling chamber and the low-pressure line at the right used for leak testing. Part of the nozzle section is shown at the left with the pressure tubes leading to the manifold board above the chamber.

increases, opening these valves. As the pressure in the settling chamber increases, the bourdon tube expands, lifting the throttle arm off the bleed nozzle. This releases the pressure on the upper diaphragm of the control system and closes the main control valve, thus decreasing the flow of control air to the regulator diaphragms. Thus, by adjusting the bourdon tube, the pressure in the settling chamber can be chosen, the valves opening and closing as the pressure in the settling chamber varies. The sensitivity of the entire system can be varied by changing the position of the bleed nozzle along the arm. From the first preliminary tests, the reducing-regulator system has held the settling chamber pressure constant within plus or minus one to two percent of the mean value.

In addition to the control system, two other adjustments can be made to change the res-
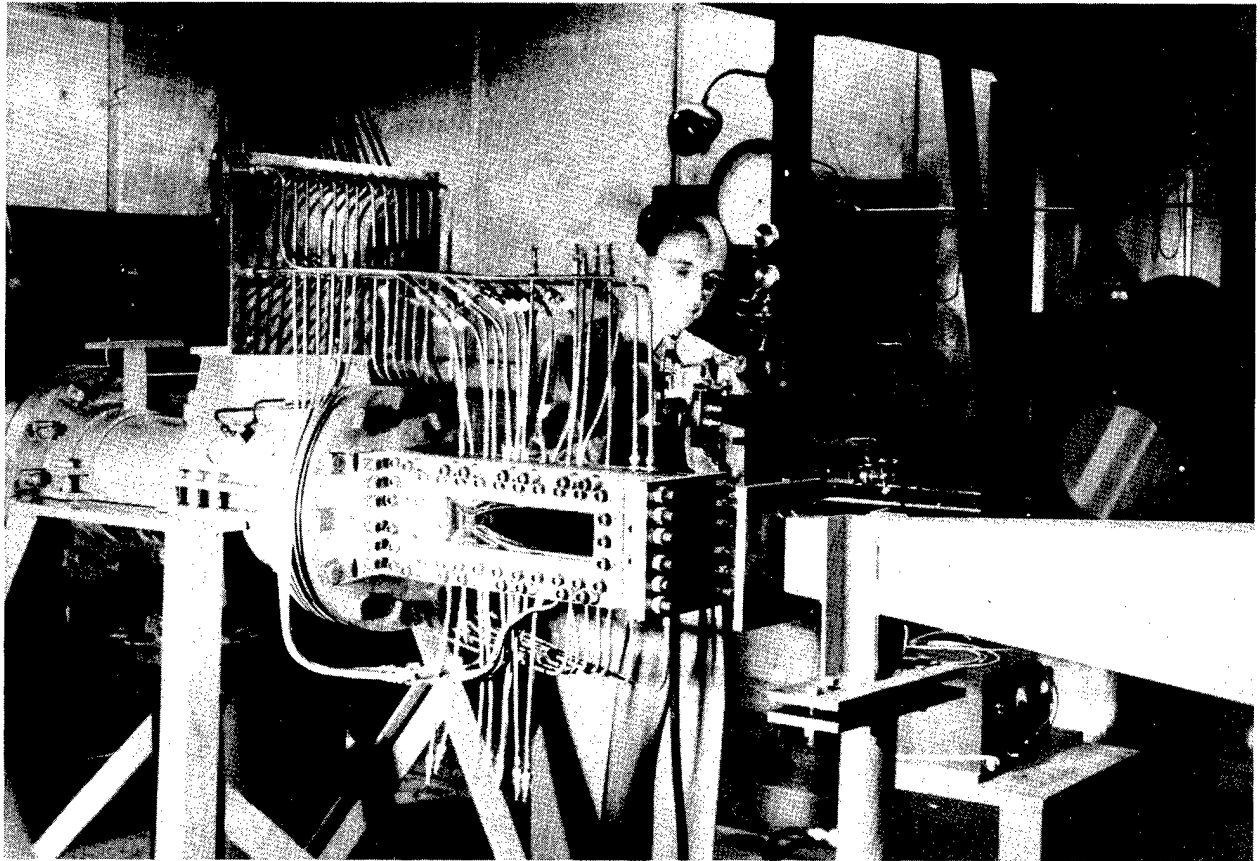
FIGURE 8

Photograph of the tunnel assembly showing the settling chamber at the left, the nozzle section designed for a Mach number of 3.01 and the first section of the diffuser at the right. The diffuser has been detached and the end of the nozzle section sealed to leak test the system.

ponse characteristics of the entire system. Adjustment of the needle valve between the damping chamber and the regulator diaphragm can change the time for a full stroke of the valve from six seconds to any longer period. Also the tension of the compression spring, which keeps the regulator valves closed when no driving pressure is available, can be adjusted to allow opening of the valve for a given driving pressure. In this particular system, the damping has been made as small as possible (fastest stroke) and the compression spring set so that about four pounds per square inch driving pressure will start to open the valves with 3000 pounds per square inch in the storage tanks.

Settling Chamber. The settling chamber is constructed of eight inch diameter copper pipe with flanges and blank ends designed for 900 pounds per square inch, Figure 7, page 10. The air enters the bottom of the chamber, passes through a ninety degree elbow, and exhausts against the

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blank back wall to give a symmetrical velocity distribution. The air then flows forward, with a maximum velocity of forty feet per second, into the settling region between the exhaust and the entrance fairing. The cast aluminum entrance fairing leads to the one by two and a half inch exit from the settling chamber. This particular fairing is used where the desired test section width is only one inch, but it can be replaced to give any section up to two and a half by two and a half inches. At the exit from the settling chamber, the Mach number is approximately 0.5. Only part of the acceleration to Mach number one was done in the settling chamber proper in order to minimize the effects of the joint between the settling chamber and the nozzle section.

Pressure taps are installed for the lines to the manometer board, the control system, and a low-pressure air supply used for leak testing. An iron-constantan thermocouple is installed at the chamber centerline just before the entrance fairing to give the stagnation temperature (Figure 7).

Nozzles and Test Section. The nozzle section is twenty-one and three-quarters inches long with glass and dural side walls, Figure 8, page 11. The nozzle blocks, which include the converging section to the sonic throat, the supersonic nozzle, and a straight walled test section, are of constant one inch width and when clamped between the side walls, act as the top and bottom walls. The section from about two inches upstream of the throat to five inches downstream from the end of the nozzle is covered by a 3/4 by 4 by 13 inch beveled glass plate set into the side walls and adjusted so that the inner surface of the glass matches the inner surface of the walls. These plates and the nozzle blocks are sealed with thin rubber strips and have been tested statically to one hundred and fifty pounds per square inch without any leakage.

The two-dimensional supersonic nozzle was designed for a Mach number of 3.01 by the method of characteristics for uniform flow at the entrance to the test section. No corrections were made for boundary layers on the walls. The nozzles themselves were made from tin-bismuth with pressure tubes cast in the nozzle. The pressure tubes were located along the centerline of each nozzle block at one-half inch intervals. The tubes in one block were, however, off-set a quarter of an inch along the nozzle, so effectively, pressure taps were located every quarter of an inch. The orifices are connected through a manifold board above the settling chamber, Figure 7, page 10, to the instruments in the panel. The test section is one inch wide and two and a half inches high with approximately eight inches of straight section before the diffuser section.

Diffuser. Because of the wide range of Mach numbers and the desire to study flows over plates, wedges, and cones, the exit conditions from the test section varies so widely that

no attempt was made to make an adjustable diffuser. For these first tests, a simple rectangular diffuser expands from the one by two and a half inch test section to eighteen by eighteen inches. A ninety degree elbow turns the air to the vertical direction, and exhausts to the atmosphere through a silencer.

Piping and Valves. All piping from the compressor to the settling chamber is of red brass. Up to the reducing-regulator valves, the piping is for 3500 pounds per square inch operation and has been hydraulically tested to 5000 pounds per square inch without failure. The charging line, one half inch diameter, runs from the compressor accumulator tank to the two inch header connecting the tanks and the reducing-regulator valves. Each tank is connected by a short one inch line to this header and a similar arrangement is used for the regulators. The low pressure part of the system, the four inch pipe, is designed for 900 pounds per square inch operation and has been hydraulically tested to 1550 pounds per square inch. The instrument lines are one quarter inch diameter copper tubing but the control lines are three-eighths of an inch diameter to permit rapid response to pressure fluctuations.

In the charging line a check valve has been inserted to allow the compressor to be worked on if necessary without blowing down the storage tanks. Two safety valves make the pressure system practically foolproof. A half inch safety valve set at 4000 pounds per square inch is attached to the high pressure two-inch header at the tank end (see Figure 3, page 7). This safety valve is intended to release excessive pressures in the tanks caused by heating-- either by the sun or fire. A second safety valve of two inch diameter is connected to the low pressure system just downstream of the regulator valves. This safety valve, set at 500 pounds per square inch, will handle all the air that the two regulator valves can pass when they are wide open and at the maximum pressure of 3500 pounds per square inch.

The two-inch high pressure valve in the line connecting the storage tanks and the regulators is normally kept closed between runs to prevent the operation of the tunnel by the accidental use of the control system. A second valve, a four inch 750 pounds per square inch steam valve (1500 pounds per square inch air) in the low pressure line is used only to cut off the air to the tunnel when other facilities are using the air supply.

Instrumentation. Pressures in the tunnel and on models are indicated on pressure gages. Three sets of gages are used, each accurate to better than one percent in its design range. Heise bourdon tube gages are used for pressures from one hundred to five hundred pounds per square inch. They are twelve inches in diameter and indicate to one pound per square foot. For pressures from twenty-five to one hundred pounds per square inch, special Kollsman aneroid gages are used. These instruments, although only three inches in diameter, have an effective scale length of almost two hundred inches since the indicator revolves twenty times

to cover the design pressure range. For pressures from twenty-five pounds per square inch to zero pressure, a special differential pressure gage, also made by Kollsman, is used. The gage is similar to the unit used for the higher pressure range, but may be used in two ways. With one side open to the atmosphere, the gage covers the zero to twenty-five pound per square inch range. One side, however, may be connected to some reference pressure, say the test section pressure. The gage will then indicate differential pressures, the absolute reference pressure being indicated by a gage of another range.

Stagnation temperature is measured by an iron-constantan thermocouple mounted in the settling chamber and indicating on a Brown potentiometer calibrated to cover the temperature range from 150 to -340°F. Barometric pressure in the test room is indicated by an aneroid type Wallace and Tiernan barometer.

All the instruments are mounted on two panels, and photographed by two eight by ten inch view cameras. The 'high-pressure' board carries all the Heise gages and in addition, a clock, the barometer, and a gage indicating the storage tank pressure. The 'low-pressure' board carries both types of Kollsman gages and the Brown temperature recorder.

The Schlieren system is a conventional two-mirror off-set system built to allow easy exchange of the four, eight, and twelve inch parabolic mirrors which are available. Since the twelve inch mirrors have the longest focal length, one hundred inches, and therefore the greatest sensitivity, these mirrors will be used for most of the tests. Two light sources are available. A G.E. type H-6 mercury arc lamp is used for a line source approximately one inch long and a sixteenth of an inch wide. This lamp can be run continuously at low voltages to align the system, to examine the flow on a ground glass screen, or to take moving pictures of the flow. When running continuously, it must be cooled by two high pressure air jets. In addition, this lamp can also be flashed in a few microseconds for Schlieren or shadow pictures. Also available is a Charters-Liebess spark, a point source which can be flashed in less than a microsecond. With either system, the picture is either observed or photographed by a five by seven inch view camera provided with a replaceable ground glass back. Shadow pictures can be taken quite easily by using the same light source as for the Schlieren system, but inserting the film in the light path immediately after it passes through the test section. The second mirror is, of course, not used in this case.

The first series of runs were intended primarily to check the operation of the equipment and instrumentation, but tests were also made to determine the effect of varying the control throttle range, the diaphragm damping, and the use of the valve positioners. A Mach number 3.01 nozzle with a one by two and a half inch test section approximately eight inches long was used for these tests. Stagnation pressures were varied from the minimum necessary to establish supersonic flow in the nozzle, approximately fifty-five pounds per square inch, to about two hundred and twenty-five pounds per square inch, with tank pressures from one thousand to twenty-five hundred pounds per square inch.

Instead of using the quick-starting technique at first, the pressure was increased slowly to the desired value in about thirty seconds. This method was used for tests covering the stagnation pressure range and then repeated, increasing the speed with which the tunnel was started. At the end of the preliminary tests, data were being recorded approximately fifteen seconds after the test was started and further work should cut this time to less than ten seconds.

The control system has worked very well from the first run. In the first runs, the tunnel was allowed to run for two to three minutes and data were recorded every twenty seconds. These results showed that the stagnation pressure was held to within plus or minus two percent of the mean value during each run. Further adjustment of the throttle setting should give constant stagnation pressures within plus or minus one percent of the mean value. Since no 'jumping' of the valve was noticeable at the start of a run, the damping needle valve was left wide open to provide the minimum amount of damping.

The most important results obtained from the preliminary tests were the variation with time of the stagnation temperature in the settling chamber and the Mach number in the test section. The temperatures experienced at the start of a run are considerably lower than those calculated from adiabatic expansion of the air in tanks, neglecting the Joule-Thomson effect. With the pressure drops experienced across the reducing-regulator valves, the Joule-Thomson effect is quite large. It accounts for a drop of approximately forty-five degrees Fahrenheit at the start of a run with a storage tank pressure of 2000 pounds per square inch and a chamber pressure of sixty pounds per square inch. The variation of the stagnation temperature with time is almost linear, Figure 9, page 16, approximately twelve to fifteen degrees per minute for the flow conditions tested. This variation will, of course, depend on the mass flow and
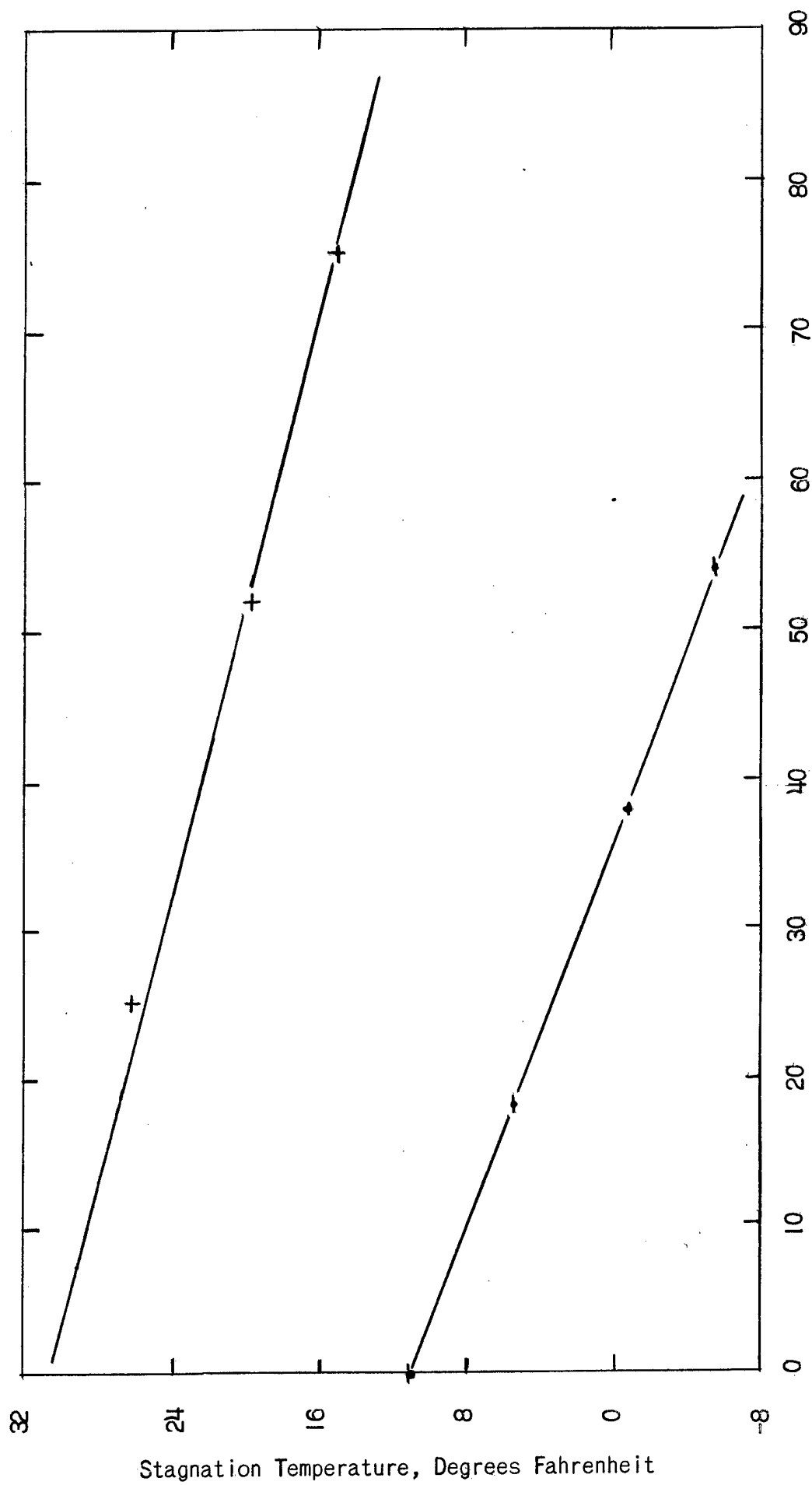
FIGURE 9. Variation of stagnation pressure with time; nozzle designed for Mach number 3.01, curve A stagnation pressure 60 psi, curve B stagnation pressure 120 psi.
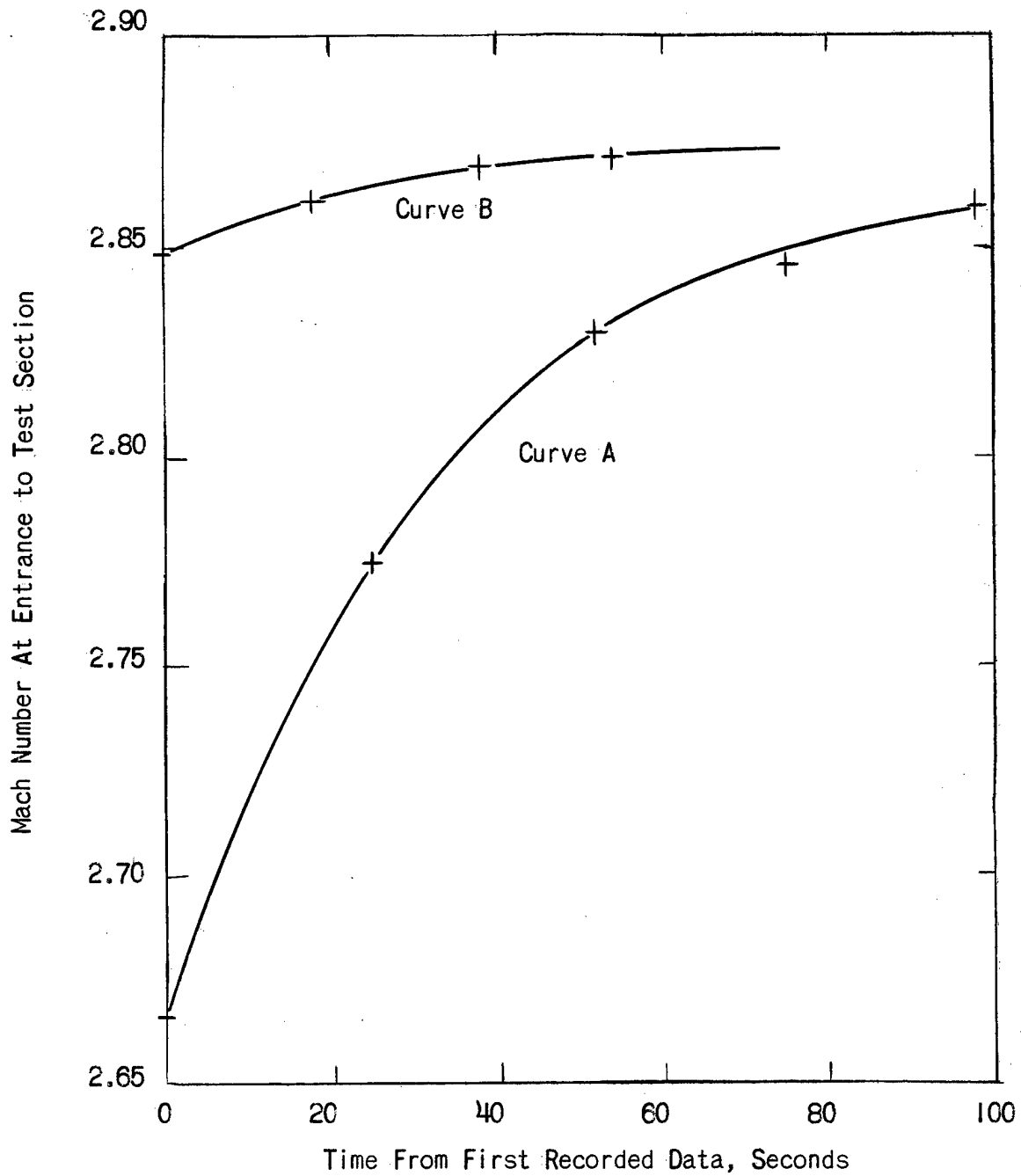
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FIGURE 10

Variation of Mach number at the entrance to the test section versus time; Curve A without precooling of the tunnel, Curve B with precooling of the tunnel.

so will increase for higher stagnation pressures and will decrease when higher Mach numbers are investigated. Stagnation temperature variations of this magnitude will have little effect on the flows in the nozzle or over test models. The temperature at the first datapoint depends entirely on how fast the tunnel is started. When the tunnel is started quickly, the temperature is higher because the air in the tanks has expanded less (lower mass flow passed before data is recorded) and so has a higher temperature.

The variation of Mach number at the test section, Figure 10, page 18, curve A was not expected, but can be explained qualitatively on the basis of heat addition to the boundary layer. When the test starts, the tunnel walls are at essentially room temperature while the air is some fifty or more degrees below room temperature in the settling chamber. There must be considerable heat transfer from the walls to the flow because the wall temperature is higher than the stagnation temperature. Work with laminar boundary layers has shown the effect of heat addition is to increase greatly the thickness of the layer. Although no theoretical work has been done with a turbulent layer, such as is undoubtedly experienced in the tunnel, the same effect should be noticeable. As the tunnel continues to run, the walls are cooled. There is less heat addition and the boundary layers thin out, which cause the Mach number to increase. The flow seems to stabilize after a run of about one minute. This time can be made very short if the regulator valves are opened slightly to allow a small flow of air to chill the tunnel walls before the test starts. This is illustrated by curve B of Figure 10. The phenomena of the thickening of the turbulent boundary layer with heat addition will be studied further in future tests where thermocouples in the walls will give quantitative information on the heat transfer.

CONCLUSIONS

The preliminary tests show that the desired control of the stagnation pressure has been obtained. Flow in the tunnel and the instrumentation reach equilibrium conditions in approximately fifteen seconds. Preliminary chilling of the tunnel by a small air flow before each test is necessary to avoid the effects of heat transfer from the walls. The operation of all equipment was satisfactory, which will now make possible the fulfillment of the proposed research program.

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May '48	Unclass.	U.S.	English	26	photos, diagrs, graphs

ABSTRACT:

The design and operation of the pilot variable density supersonic wind tunnel of Princeton University's Aeronautical Engineering Laboratory are discussed in detail. The tunnel, with a 1 x 2-1/2 in. test section, is designed to operate with stagnation pressures up to 500 psi at Mach numbers from 1.5 to 5.0. It is of the blow-down type, but uses a pressure control system to keep the stagnation pressure constant during test. The main test result was the observation of a transient at starting due to heat transfer effects. This transient can be almost completely eliminated by precooling the tunnel with a small amount of cold air. Operation of all equipment was satisfactory.

DIVISION: Wind Tunnels (17) SECTION: Design and Description (1)	SUBJECT HEADINGS: Wind tunnels, Supersonic - Design (99130); Project Squid (75406); Wind tunnels - Operation (99115); Wind tunnels - Temperature control (99117.9); Wind tunnels - Pressure boxes (9911528)
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DISTRIBUTION: Copies of this report obtainable from CADO.   (1)

DIVISION: Wind Tunnels (17) SECTION: Design and Description (1) ATI SHEET NO.: R-17-1-11	SUBJECT HEADINGS: Wind tunnels - Design (99112); Wind tunnels - Operation (99115); Project Squid (75406)